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On the profile of intense high-altitude auroral electric fields at magnetospheric boundaries

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Abstract. The profile of intense high-altitude electric fields on auroral field lines has been studied using Cluster data. A total of 41 events with mapped electric field magnitudes in the range between 0.5–1 V/m were examined, 27 of which were co-located with a plasma boundary, defined by gradients in particle flux, plasma density and plasma temperature. Monopolar electric field profiles were observed in 11 and bipolar electric field profiles in 16 of these boundary-associated electric field events. Of the monopolar fields, all but one occurred at the polar cap boundary in the late evening and midnight sectors, and the electric fields were typically directed equatorward, whereas the bipolar fields all occurred at plasma boundaries clearly within the plasma sheet. These results support the prediction by Marklund et al. (2004), that the electric field profile depends on whether plasma populations, able to support intense field-aligned currents and closure by Pedersen currents, exist on both sides, or one side only, of the boundary.

Keywords. Magnetospheric physics (Auroral phenomena; Electric fields; Magnetosphere-ionosphere interactions)

1 Introduction

Quasi-static electric fields are, together with Alfvén waves, responsible for the acceleration of auroral particles and the energy transport towards and away from the auroral ionosphere. Several theories have been proposed to explain the electric field parallel to the magnetic field, e.g., theories involving strong double layers (Block, 1972), weak double layers (Temerin et al., 1982), Alfvén waves (Song and Lysak, 2001), anomalous resistivity (Hudson and Mozer, 1978) and magnetic mirror supported fields (Knight, 1973; Chiu and Schulz, 1978). Recent observations confirm earlier studies that strong double layers are responsible for at least part of the parallel electric fields, both in the primary and return current regions (Andersson et al., 2002; Ergun et al., 2002). The quasi-static electric fields associated with strong double layers are usually intense, $|E_\perp|>100$ mV/m (mapped to the ionosphere for reference). Converging electric fields in the primary current region, with an upward parallel component, accelerate electrons downward and ions upward. This acceleration region is found approximately between 5000 and 8000-km altitude, possibly in the form of two transition layers separated by the auroral cavity (Ergun et al., 2000). The acceleration of electrons (upward) and ions (downward) in the return current region region takes place at lower altitudes. Diverging electric fields (downward parallel component) have been observed down to altitudes of 800 km (Marklund et al., 1997). Signatures of bipolar, converging and diverging, perpendicular electric field, consistent with U-shaped potential structures, have been found at high altitudes (4–7 R_E geocentric distance) by Cluster in both the primary and return current region (Figueiredo et al., 2005; Johansson et al., 2005). Monopolar electric fields, indicating S-shaped potential structures (e.g., Chiu et al. (1981)), are also associated with particle acceleration and have been observed both at low and high altitudes (e.g., Mizera et al. (1982), Marklund et al. (1997) and Johansson et al. (2004)). The bipolar electric field perpendicular to the magnetic field displays two oppositely directed enhancements, while the monopolar electric fields lack the reversal in the perpendicular component. A difference between the two types of electric fields can also be seen in the potential (the electric field integrated along the spacecraft trajectory). A monopolar electric field is consistent with a step in the potential, while a bipolar electric field is consistent with a "hill" (diverging electric field) or a "valley" (converging electric field).

An interesting question concerns the differences between the two types of electric fields; why is the profile of intense electric fields sometimes bipolar and sometimes monopolar?

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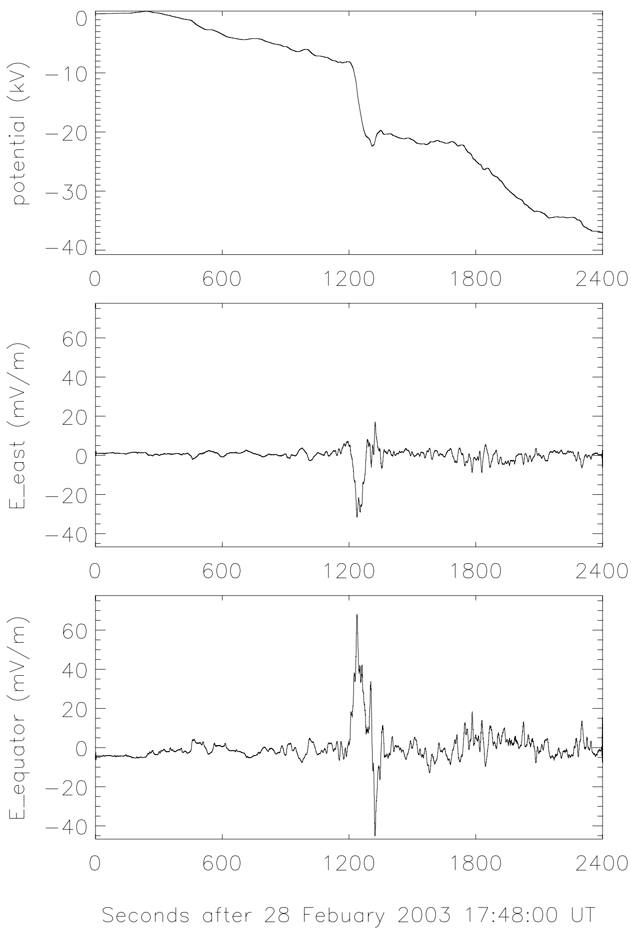

Fig. 1. Example of a monopolar electric field structure (at approximately 18:08 UT or 1200 s into the plot) from 28 February 2003. The first panel displays the integrated potential along the spacecraft trajectory. The last two panels display the eastward and equatorward directions of the electric field in local values.

To answer this question, differences, if any, in location, occurrence and plasma surroundings must be determined.

A possible answer might be found by considering the associated current system, as proposed by Marklund et al. (2004). This consists of downward and upward field-aligned currents connected by Pedersen and Hall currents in the ionosphere, forming a closed current system driven by some generator at the high altitude end. Marklund et al. (2004) proposed that the profile of the intense auroral electric field and potential, typically located at a plasma boundary, depends on the capability of the different plasma populations, on the two sides of the boundary, to support significant field-aligned currents (FACs) and ionospheric current closure. If the plasma populations on both sides of the boundary fulfill this requirement (case 1) the electric field profile should be bipolar. If, on the other hand, only one of the two plasma populations, separated by the boundary, fulfills this requirement (case 2) the electric field profile should typically be monopolar. Marklund et al. (2004) based this prediction on four intense electric field events observed by Cluster in the auroral return current region, two of which were bipolar, diverging electric field structures, occurring at the boundaries within the plasma sheet (PS, case 1), and the other two being monopolar structures, occurring at the nightside polar cap (PC) boundary (case 2).

Other mechanisms are possible, one discussed by Roth et al. (1993) treat a situation where two different plasma populations are in contact with the boundary parallel to the magnetic field. If the two populations have different temperatures the ion gyroradii will be different and the colder plasma close to the boundary will have a surplus of positive charges. On the other side of the boundary, in the hotter plasma, there will be a surplus of negative charges. This will give raise to an electric field pointing across the boundary. Roth et al. (1993) showed that such electric fields can be associated with potential differences and scale sizes consistent with discrete auroral arcs. At the PC boundary, such monopolar electric fields would be directed equatorward. If there is, within the PS, a filament of enhanced or reduced plasma temperature, this mechanism might set up bipolar electric fields.

The two plasma populations in the model by Roth et al. (1993) have different temperatures and densities, so there is not necessarily a pressure gradient across the boundary. Pressure gradients have been discussed in connection to auroral arc formation, e.g. by Galperin et al. (1992).

Plasma boundaries can be characterized in a number of ways, such as by the variations in particle flux, plasma density and plasma temperature. The topological change of the magnetic field at the PC boundary, from open to closed field lines, is associated with changes in such parameters (see Doe et al. (1997) and references therein). The PC (open field lines) is characterized by a low density isotropic plasma and polar rain electrons. The plasma sheet boundary layer (PSBL), the most poleward part of the PS (closed field lines), is a hotter, denser and more structured region. The PC boundary is quite easily identified in electron energy-time spectrograms. In this study, a separation is not made between the PSBL and the central plasma sheet (CPS), the whole region is referred to as the PS. Plasma boundaries, or variations in the plasma populations, within the PS are commonly seen but the associated variations are typically less distinct than those at the nightside PC boundary.

This study contains 41 intense electric field events observed by Cluster, including both converging and diverging bipolar as well as monopolar electric field structures and observations from both the auroral primary and return current regions. The locations of the two type of electric fields are determined relative to the plasma surroundings. The relation between the potential profile of intense auroral electric fields and plasma boundaries is further investigated.

For the events where the separation of the Cluster satellites was not too large, the stability of the encountered structures is also examined.

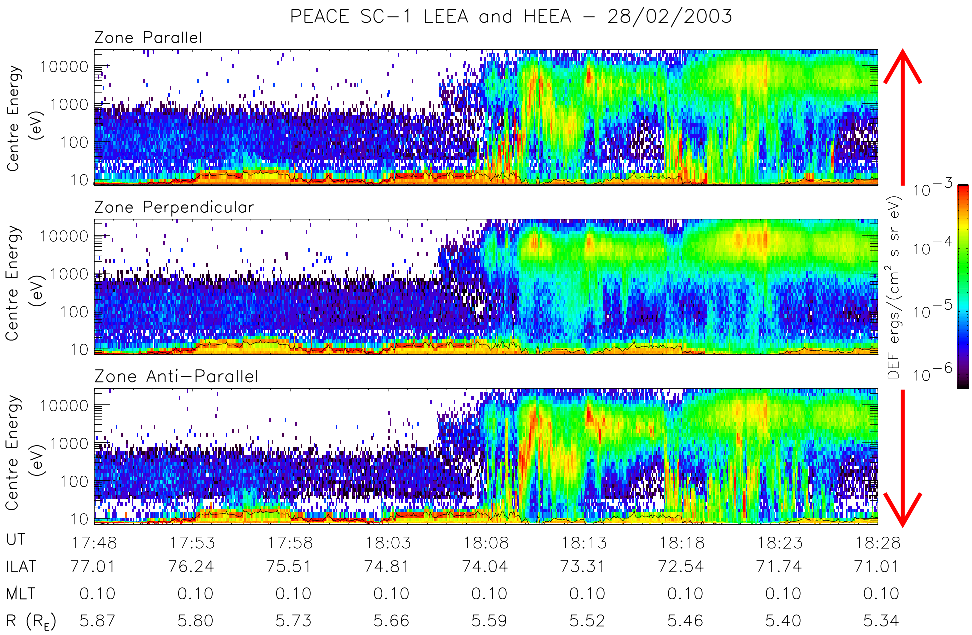

Fig. 2. PEACE data for the same period as in Fig. 1. The three panels are electron energy-time spectrogram, displaying the energy flux in the directions parallel, perpendicular and anti-parallel to the magnetic field. Since this event occurs in the southern hemisphere, up-going electrons are found in the first panel and down-going electrons in the third panel, as indicated with arrows.

2 Method

The events used in this study are a subset of events from a larger statistical study on intense electric fields (Johansson et al., 2005) measured by the Cluster EFW instrument (Gustavsson et al., 1997). From the database obtained in that statistical study, events in the range 0.5–1 V/m (values mapped to the ionosphere for reference), were selected and inspected manually. Events with clear bipolar or monopolar signatures were further selected for closer investigation. The signatures of an monopolar event are a single excursion in the electric field and a net change (a step) in the potential. Bipolar electric field events were identified as pairs of oppositely directed excursions in the electric field and by no or only a small net potential difference. Converging and diverging bipolar electric fields are seen as “valleys” and “hills” in the potential, respectively. A number of event studies (Marklund et al., 2001, 2004; Johansson et al., 2004; Figueiredo et al., 2005) of intense electric field events have been presented and they are included in this study, yielding a total number of 41 events.

The location of the events relative to the plasma surroundings were determined by manually inspecting particle data from the PEACE (Johnstone et al., 1997) and CIS (Rème et al., 1997) instruments. The plasma populations and boundaries were investigated with respect to densities and plasma β (including both proton and electron pressure, $\beta = p_{\text{particle}}/p_{\text{magnetic}} = (p_e + p_p)/p_{\text{magnetic}} \approx \mu_0(n_e kT_e + n_p kT_p)/B^2$), as well as in the form of energy-time spectrograms.

The FACs associated with the electric field structures have been determined using the magnetic field measured by the FGM instrument (Balogh et al., 1997). A fourth degree polynomial was fitted to the measured magnetic field and subtracted from the measured value. The resulting residual magnetic field is associated with small-scale FACs, 26–94 km in local values (not mapped to the ionosphere) for the events in this study.

3 Results

Examples are given below of a monopolar electric field event observed at the PC boundary and a bipolar electric field event observed within the PS, both observed by Cluster. A summary of the results for all 41 events is also given.

3.1 Example of a monopolar electric field event

Figure 1 displays a monopolar electric field event observed by Cluster 1 on 28 February 2003 in the Southern Hemisphere. The spacecraft is moving equatorwards and encounters the electric field structure at approximately 5.6 R_E geocentric distance, close to magnetic midnight, at approximately 18:08 UT and at –74.4deg CGLat (Corrected Geomagnetic Latitude). ACE observations show that the IMF turned southward for a short period around 17:00 UT but that it was otherwise northward directed before and during this event.

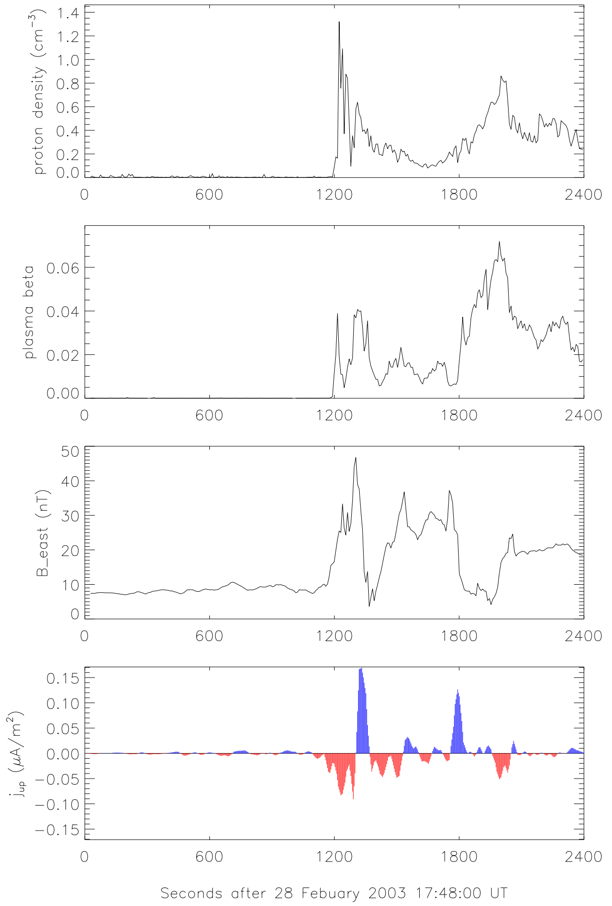

Fig. 3. The first panel displays proton density and the second panel displays the calculated $\beta = p_{\text{particle}}/p_{\text{magnetic}} \approx \mu_0 (n_e k T_e + n_p k T_p)/B^2$. The fourth panel displays the FAC calculated from the residual magnetic field, displayed in the third panel. Upward directed FACs are positive (blue) and downward FACs are negative (red). The time period is the same as in Fig. 1.

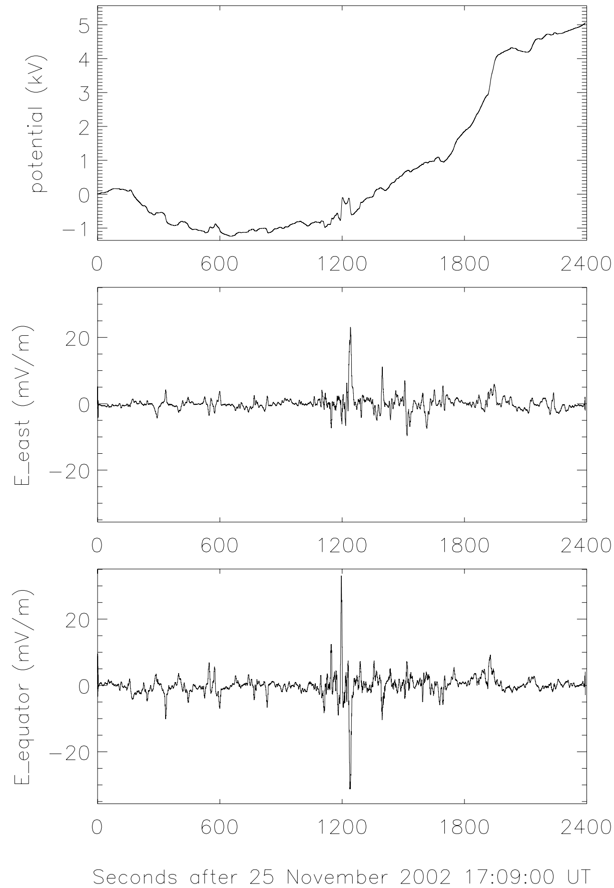

Fig. 4. Example of a bipolar electric field structure (marked by vertical lines) from 25 November 2002. The panels are the same as in Fig. 1. The values are local.

Data are shown for the period 17:48–18:28 UT. The observations are presented in the following way. The first panel of Fig. 1 shows the potential (the electric field integrated along the spacecraft trajectory), while the second and third panels show the eastward and equatorward components of the electric field, respectively. All values are local and not mapped to the ionosphere. Figure 2 displays three panels of electron energy-time spectrograms for the directions parallel, perpendicular and antiparallel to the background magnetic field (directions of the electrons are indicated by the red arrows) from the same time period as in Fig. 1. Figure 3 displays proton density and β in the two first panels. The FAC in the fourth panel is calculated from the eastward component of the residual magnetic field, displayed in the third panel. Upward directed FACs are positive (blue) and downward FACs are negative (red).

The integrated perpendicular potential signature is a distinct negative step, consistent with a monopolar, roughly equatorward electric field and indicative of a S-shaped potential structure, with a perpendicular potential close to 12 kV. The magnitude of the electric field peak in the equatorward component is 70 mV/m. A weaker asymmetric bipolar signature (not included in the statistical study) is observed in the equatorward component of the electric field approximately one minute after the monopolar peak. The potential associated with this electric field ($\sim$1 kV) is a small fraction of the potential step associated with the monopolar electric field. Poleward of this structure the electric field is quiet, while some activity is seen on the equatorward side.

The electron energy-time spectrograms in Fig. 2 display a thin plasma in the poleward half of the plot. A weak electron flux enhancement is seen between 17:53 UT and 17:58 UT but otherwise this region is typical of the PC. The plasma region seen equatorward of this is characterized by a highly structured and variable electron flux typical of the poleward part of the PS. The electric field peak is located at the distinct boundary between the two regions.

The sharpness of the boundary in terms of density, β-value and FACs is illustrated in Fig. 3. The density, β-value and FACs increases significantly from the poleward to the equatorward side of the boundary. A very low proton density ($<0.01\,\mathrm{cm}^{-3}$) is detected in the PC region. An abrupt increase of the proton density to $\sim 1\,\mathrm{cm}^{-3}$ is seen at the boundary after which the proton density settles down to a value of $<0.4\,\mathrm{cm}^{-3}$, clearly above the level in the PC. The whole interval displayed is characterized by a low β ($\ll 1$). However, a sharp increase is observed in the β-value at 18:08 UT (1200 s into the plot) and is followed by variations in β between ~ 0.01 and ~ 0.07. The sharp increase in β also indicates a particle pressure gradient at the boundary, since the magnetic pressure is rather constant in this event.

The last two panels in Fig. 3 show that the monopolar electric field (~ 1200 s into the plot) is associated with a downward FAC (negative and shown in red) with a maximum magnitude of $0.09\,\mu\,\mathrm{A/m}^2$. Next to this current an upward FAC (positive and shown in blue, maximum magnitude $0.17\,\mu\,\mathrm{A/m}^2$) is observed, correlated with the less intense bipolar electric field. The upward FAC appear to balance the downward FAC, indicating a local closure. Note that intense FACs are only found on the equatorward side of the boundary.

In Fig. 2, 1-keV electrons with a low number flux are observed between 18:06–18:08 UT. It might be argued that this electron population is trapped on closed field lines, although proton density and β indicates a sharp boundary at 18:08 UT.

To summarize, there is a sharp plasma boundary at approximately 18:08 UT, as evident from proton densities, β-value and FAC variations, with a much denser and more structured plasma region on the equatorward side, forming the poleward part of the PS. Associated with this boundary is an intense electric field. This event illustrates a monopolar electric field occurring at a sharp plasma boundary, characterized by very different plasma populations on either side.

3.2 Example of a bipolar electric field event

A bipolar electric field structure was observed by Cluster 1 on 25 November 2002, around 17:29 UT. At this time, the spacecraft was travelling poleward in the Northern Hemisphere and encounters the electric field structure at $5.3\,\mathrm{R}_E$ geocentric distance, at 75.7 CGLat and at 5.7 MLT. The IMF had been southward directed but turned northward between 16:50–18:00 UT (observed by ACE).

Figure 4 shows 40 min of electric field data, together with the integrated potential, starting at 17:24 UT and using the same format as Fig. 1 (all values are local). The bipolar structure is observed in the equatorward component of the electric field and occurs in the beginning of a region of small amplitude disturbance. The enhancements in the electric field are $\sim \pm 30$ mV/m. The peak in the potential ($\Delta V \sim 0.6$ kV) (approximately 1200 s into the plot) is indicative of a diverging bipolar electric field. To better present the bipolar electric field, a 8-min zoom, starting at 17:26 UT, is displayed in Fig. 5.

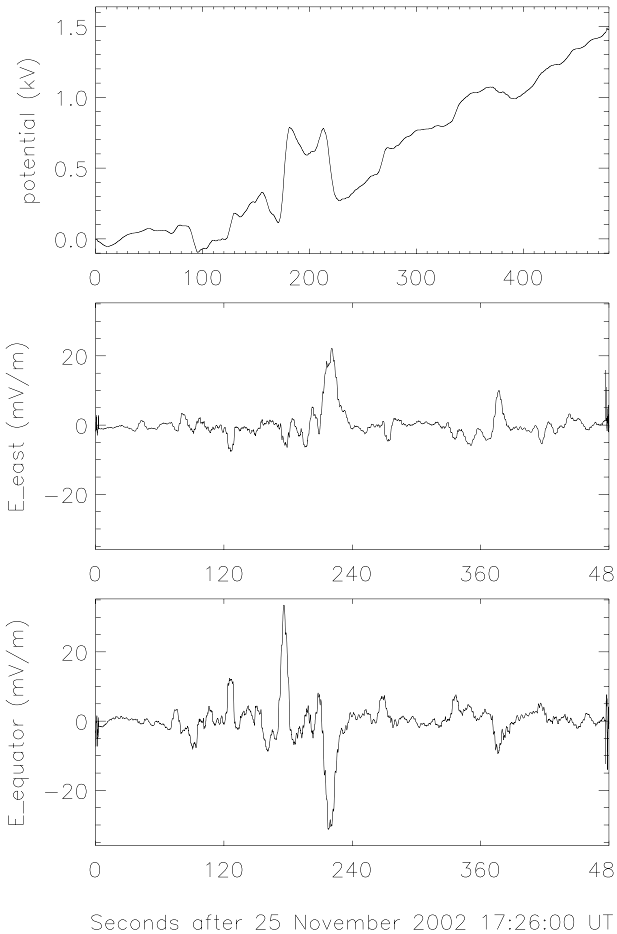

Fig. 5. The same bipolar event as in Fig. 4 but this time only 8 min of data.

Figure 6 displays PEACE electron data for the period 17:09–17:49 UT, using the same format as in Fig. 2. The shorter 8-min interval presented in Fig. 5 is marked by vertical red lines in the PEACE energy-time spectrograms. A homogeneous, isotropic and relatively dense plasma population is encountered first. At 17:28 UT the Cluster spacecraft enters into a more structured region. The intense bipolar electric field structure is encountered somewhat poleward of this boundary. A less structured and thinner plasma with smaller flux is observed after 17:40 UT.

These three regions are also seen in Fig. 7 displaying proton density, β, the eastward component of the residual magnetic field and FAC in the same form as Fig. 3. The shorter 8-min period of Fig. 5 is marked by vertical red lines. A gradual decrease in density is seen as the spacecraft is moving poleward, from $1.5\,\mathrm{cm}^{-3}$ to $\sim 0.1\,\mathrm{cm}^{-3}$. The β parameter is low ($\ll 1$) during the entire interval and decreasing, with the three different plasma regions well defined. The FAC is

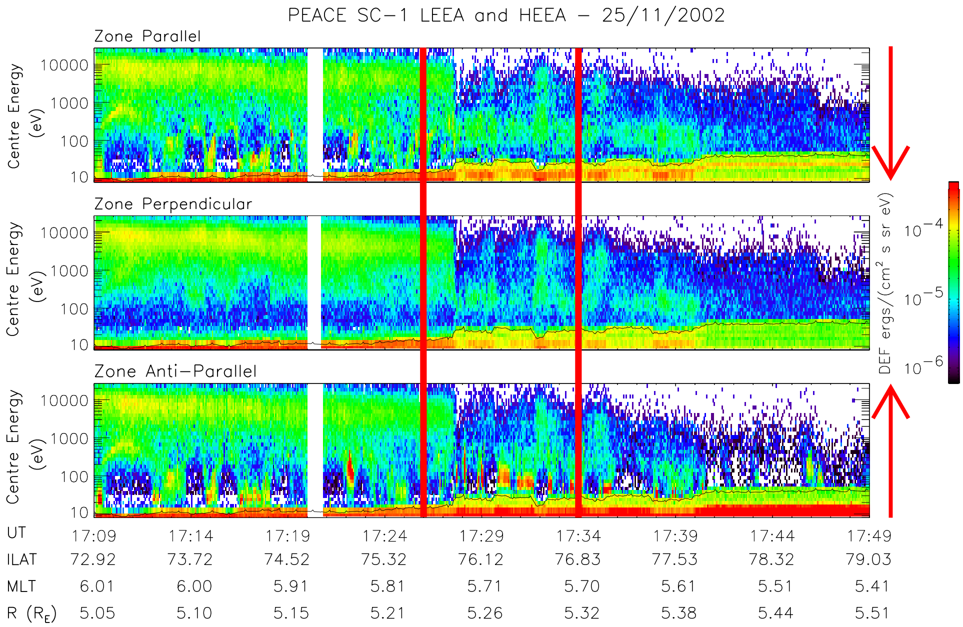

Fig. 6. Overview of PEACE data for the bipolar electric field event in Fig. 4. The panels are the same as in Fig. 2. However this event occurs in Northern Hemisphere, so down-going electrons are found in the first panel and up-going electrons are found in the third panel, as indicated with arrows. The vertical red lines mark the shorter interval displayed in Fig. 5.

structured with both upward and downward currents. The magnitudes of the FACs are decreasing in the poleward part of the displayed region. During the shorter 8-min interval, the FAC is dominantly downward directed with a maximum magnitude of 0.028 μ A/m^2. Upward FACs are observed on both sides of this region, with the wider and more intense (up to 0.016 μ A/m^2) region being the equatorward one. However, they appear not to balance the downward FAC dominating in the shorter region. This may be due to curved current sheets, non-local closure or time variation.

The bipolar electric field structure is located close to but somewhat poleward of the first plasma boundary, encountered at 17:28 UT and located well within the PS. The particle variations at this boundary, e.g., the particle pressure gradients indicated by the variations in β, associated with the bipolar electric field signature, are less than those associated with the previous monopolar electric field.

To summarize, two plasma boundaries are encountered. The one associated with the bipolar electric field is a boundary between plasma populations with similar characteristics. This illustrates a bipolar electric field occurring at a plasma boundary within the PS.

3.3 Summary of results

After manually inspecting 41 intense electric field events, 27 (most found within the statistical auroral oval) were determined to be bipolar or monopolar electric field structures occurring either at a sharp plasma boundary (the nightside PC boundary) or at some less distinct plasma boundary within the PS. The results are summarized in Table 1. For some of the events, the plasma surroundings were ambiguous (10 events) and they are labelled as unclear in Table 1. The remaining 4 events excluded from this study occurred in the polar cusp. The trends for the two kind of electric field signatures are clear.

All but one of the total 11 monopolar events occurred at a nightside PC boundary. Thus, the relation between the distinct plasma boundary associated with the PC and monopolar events is well supported from this study. The exceptional monopolar event not located at the PC boundary, was observed at a totally different local time (7.8 MLT) as compared to the other monopolar events, which were all located within the evening and midnight local time sectors (16–02 MLT).

All the bipolar events are found at plasma boundaries within the more or less structured PS. These boundaries have not been specified here. Common for all of them are that they are much less distinct than the PC boundary. Therefore it is here only stated that the bipolar events do not occur at the PC boundary, but rather at some less distinct plasma boundary or irregularity within the PS. A rather even spread in MLT was found for the bipolar events, although no events were found close to noon (08–15 MLT).

Table 2 displays observed values of proton density and β in the PC and PS, and also the average variations at the boundaries. There is some overlap in proton density and β for the PC and the PS but when the values of these parameters are low in the PS, then they are even lower in the PC. The

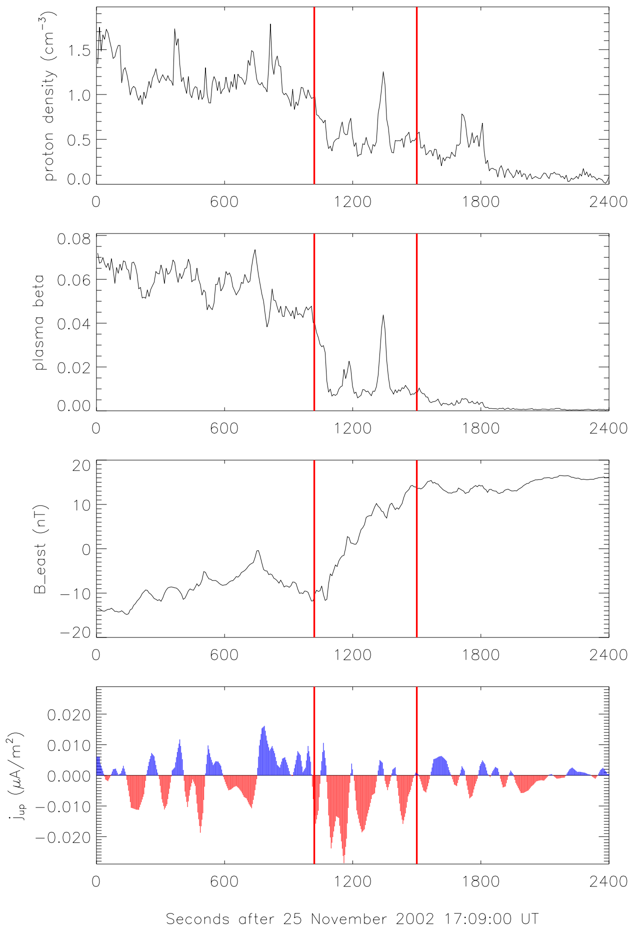

Fig. 7. Proton density, β, residual magnetic field and FAC are displayed in the same format as in Fig. 3. The vertical red lines marks the 8-min interval of Fig. 5.

Table 1. Summary of the results. A total of 41 events have been investigated, 27 of those occurred at either the polar cap (PC) boundary of the plasma sheet (PS) or within the plasma sheet.

	monopolar	bipolar	total
PC boundary of PS	10	0	10
PS	1	16	17
cusp	3	1	4
unclear	6	4	10
total	20	21	41

Table 2. Observed values of proton density, n_{H^+}, and the parameter $\beta = p_{\text{particle}}/p_{\text{magnetic}} \approx \mu_0(n_e kT_e + n_p kT_p)/B^2$ and their average increase at different plasma boundaries.

	n_{H^+}	β
Value in PC	$<0.3\,\text{cm}^{-3}$	<0.0075
Increase at PC boundary (%)	563	706
Value in PS	$0.1–3.0\,\text{cm}^{-3}$	0.004–0.13
Increase at boundary within PS (%)	153	253

Table 3. FAC directions for the investigated events.

	upward FAC	downward FAC
monopolar	5	6
converging bipolar	7	0
diverging bipolar	0	8

variations and particle pressure gradients, as indicated by β (the magnetic pressure is rather constant in all these events), are clearly smaller at boundaries within the PS as compared to the variations seen at the PC boundary. This shows that the plasma populations on the two sides of a boundary within the PS are generally more similar than the plasma populations on different sides of the PC boundary.

The FACs have been calculated for all the 27 monopolar or bipolar events found at some plasma boundary within the PS or at the PC boundary. Both upward and downward directed FACs were found, see Table 3. The directions of the FACs were, for the bipolar events, consistent with the electric field, converging or diverging. Within the PC, no significant FACs were observed. In one event the FAC was small and its direction unclear. The downward FACs occurred between 65 and 76° CGLat and in the late evening to morning sectors (20–08 MLT). Upward FACs were mostly found in the ranges 15–21 MLT and 72–77° CGLat. This can be seen in Fig. 8 where the distribution of upward (blue) and downward (red) FACs are plotted together with a statistical oval (Kauristie, 1995). Although there was some overlap, especially in the evening sector, the distributions of downward and upward FACs show a tendency of being located within the large scale Region 1 current system. In the statistical study by Johansson et al. (2005), from which these events were selected, a general trend towards small-scale FACs having directions consistent with the large scale Region 1 currents and, at higher latitudes, with the NBZ-current system (Iijima and Shibaji, 1987) prevailing during northward IMF conditions.

The scale sizes (mapped to the ionosphere) of the encountered electric field structures were typically in the range 1–5 km, consistent with earlier statistical results (Johansson et al., 2005), but with a maximum scale size of 27 km. No difference between the scale sizes of monopolar and bipolar events could be observed.

Table 4. The number of spacecraft N that observed a similar structure, total time separation T between these observations and type of electric field structure.

event	N	T (s)	type
14 Jan 2001	3	180	diverging bipolar
14 Feb 2001	4	320	diverging bipolar
28 Apr 2001	4	182	converging bipolar
3 Dec 2001	3	63	diverging bipolar
15 Apr 2002	4	40	monopolar
27 Apr 2002	3	22	monopolar
19 May 2002	4	62	monopolar
10 Jul 2002	3	738	converging bipolar
25 Nov 2002	2	160	converging bipolar

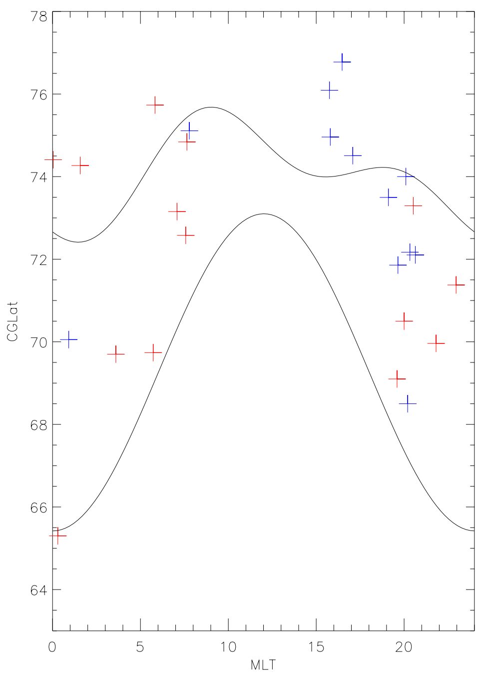

Fig. 8. A scatter plot showing the MLT and CGLat distributions of upward (blue) and downward (red) FACs associated with the monopolar and bipolar electric field events found at some plasma boundary within the PS or at the PC boundary. The black lines indicate a statistical auroral oval.

For 9 events from 2001 and 2002, including both monopolar and bipolar events, where the separations between the Cluster spacecraft were relatively short, the stability of the encountered electric field events and plasma boundaries have been investigated, see Table 4. The time differences between the observations made by consecutive spacecraft should be considered with care; they only give a minimum life-time of

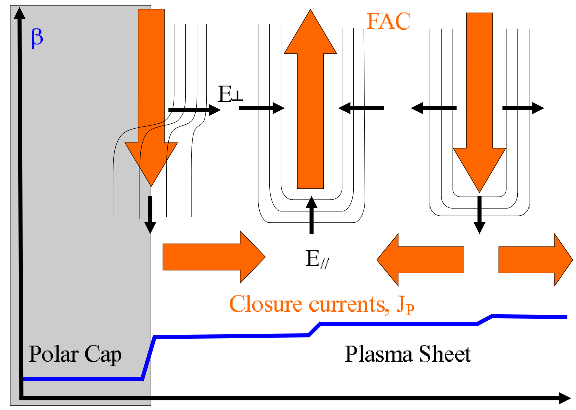

Fig. 9. A sketch illustrating a possible relation between plasma populations, currents and intense electric fields as discussed in the text. The polar cap is shaded grey while the white region is the plasma sheet. FACs and closure currents are illustrated by vertical and horizontal the red arrows, respectively. The black arrows are the perpendicular and parallel electric fields. The variations in the plasma populations are represented by an idealized plot of β (blue line). β is increasing at the polar cap boundary but β can both increase and decrease inside the plasma sheet.

the structures and sometimes the configuration of the satellites does not allow the evolution of the structure to be followed. There is quite a wide range (22–738 s) in the minimum life-times of these structures. The 14 January 2001 event (Marklund et al., 2001) is the only event where the growth and decay of the structure can be followed, with a life-time somewhere in the range 180–280 s.

4 Discussion

In this statistical study, 41 intense electric field events with mapped magnitudes ranging between 0.5 and 1 V/m were examined. 27 of the investigated events were associated with a more or less clear plasma boundary. 10 of these had monopolar electric field profiles, with the electric fields typically directed equatorward, and occurred at a distinct plasma boundary (the nightside PC boundary). Only 1 monopolar event occurred at a less distinct plasma boundary (within the PS), but in a totally different MLT sector than for the rest of the monopolar events. All the 16 bipolar events occurred in a plasma surrounding having relatively similar plasma populations on both sides of the boundary (within the PS).

Figure 9 is a qualitative illustration of a possible relation between plasma populations, currents and the profiles of intense electric fields. The vertical red arrows represent FACs and the horizontal red arrows the closure currents. Potential contours are drawn in black and the directions of the parallel and perpendicular electric fields are shown with black arrows. The PC is shaded grey. The variations in plasma parameters (density, temperature) are represented by β (blue line), which increases at the polar cap boundary. The smaller variations in β inside the plasma sheet could be both positive and negative. The requirement of current closure at low altitudes for the FACs together with differences in the capability of such closure at boundaries could determine the signature of the electric field. If so, then at a sharp boundary with a steep particle pressure gradient, such as the PC boundary, a FAC current is more likely to be closed on the side with higher density (the equatorward side), leading to a electric field pointing in mostly one direction. As a contrast, a FAC within the PS can be closed in two directions. At a boundary within the PS, both sides are characterized by relatively dense and hot plasma (compared to the PC plasma) and the particle pressure gradients are less steep. Quantitative values of boundary characteristics are given in Table 2. With currents being able to close in two directions, the electric field signatures will be bipolar, either converging or diverging.

The events in this study are all intense (0.5–1 V/m, values mapped to the ionosphere). However, also less intense bipolar and monopolar electric fields (0.15–0.5 V/m, mapped values) have been found in other studies (e.g., Johansson et al. (2005)) and it is possible that the same mechanism applies for those events.

Burke et al. (1994) observed sharp equatorward directed electric field peaks at the PC boundary in DE-2 data at altitudes of 450–900 km. They could reproduce this signature in a simple model, assuming that the conductivity increased linearly from the PC to the PS and by demanding current continuity. Their result is similar to what has been observed for the monopolar electric field at the PC boundary in this study at higher altitudes (4–7 R_E geocentric distance). Burke et al. (1994) reported only downward FACs in the most poleward part of the PS. However, in this study, both small-scale upward and downward FACs are found to be associated with the most poleward electric field signatures, i.e., the monopolar electric fields (see Table 3).

According to Roth et al. (1993), when two plasma populations with different temperatures and densities are in contact with the boundary parallel to the magnetic field, an electric field pointing across the boundary will be created. The cause of the electric field is a charge separation set up by the different ion gyroradii in the two plasma populations. Roth et al. (1993) showed that such electric fields can be associated with potential differences and scale sizes consistent with discrete auroral arcs. At the sharp PC boundary, this effect would result in a monopolar electric field pointing equatorward. The monopolar electric fields observed at the PC boundary in this study are more often directed equatorward than poleward. This mechanism might also be responsible for bipolar electric fields at less distinct boundaries within the PS. Two oppositely directed perpendicular electric fields might be the result of a filament of enhanced or reduced plasma temperature.

Field aligned resonances (FLRs) have been proposed as a possible producer of discrete auroral arcs (e.g., Samson et al. (2003)). Their magnetic and electric field topologies resemble the characteristic features of the auroral current system with upward and downward FACs, connected via Pedersen currents (Greenwald and Walker, 1980). Due to the characteristics of the FLRs in the auroral region, with alternating directions of FACs and both monopolar and bipolar electric field signatures, it is possible that a part of the observations in this study is associated with FLRs.

The PSBL is a region were Alfvén waves have been observed. In one event, during the main phase of a major geomagnetic storm, simultaneous Polar and FAST measurements indicated downward acceleration of electrons associated with Alfvén waves (Dombeck et al., 2005). Energetic substorm-related waves have been found in the primary current region (Keiling et al., 2000, 2005). The monopolar and diverging or converging bipolar electric field structures studied here are found both in the primary and the return current regions and they are not exclusively related to substorm activity.

5 Conclusions

A correlation between sharp plasma boundaries and monopolar electric fields has been observed in this study. None of the bipolar electric fields were found at the PC boundary.

This suggests that the profile of the intense electric fields at the PC boundary might be determined by the fact that only the equatorward plasma population is able to support field-aligned currents and closure by Pedersen and Hall currents.

On the other hand, if the plasma populations on both sides of a boundary are able to support current closure, then the electric field signature is more likely to be bipolar. Such electric fields are observed within the PS.

The results of this study, including intense converging and diverging bipolar, as well as monopolar, electric fields from both the primary and return current regions, support the model given by Marklund et al. (2004), based on two diverging bipolar and two monopolar electric field events observed in the return current region.

The observed lower limit stability of the structures, approximately half a minute to 10 min, is in agreement with what has been found in earlier Cluster event studies (Marklund et al., 2001, 2004; Johansson et al., 2004; Figueiredo et al., 2005).

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